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Title: Subatomic Particles, Radiation Effects

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Subatomic Particles, Radiation Effects

Overview

- Single-event effects: types
- Indirect ionization
- Cross-section
- Range
- Angular effects
- Poisson

Single-event effects

- Unlike accumulated dose effects, single-event effects could cause transient failures with only one particle
  - Cross-section, which is an areal measurement to the sensitivity of a particular SEE, often determines how many particles to cause the SEE
  - Since the sensitive area doesn't exist continuously across the part, there are areas where particles can hit and not cause the effect
  - “time-space Poisson effects”

SEE: the transient

- Measurable effects in an “off” transistor
- Particle strike liberates e-h pairs
- E-h pairs cause charge generation
- Charge generation causes the transistor to turn “on” temporarily
- Ion->charge->e-h pairs->current->signal

SEE: the transient

- Even though the particle is much smaller than the transistor, the charge generation cloud can be much larger than one or many transistors
  - Based on feature size
  - The LET of the particle

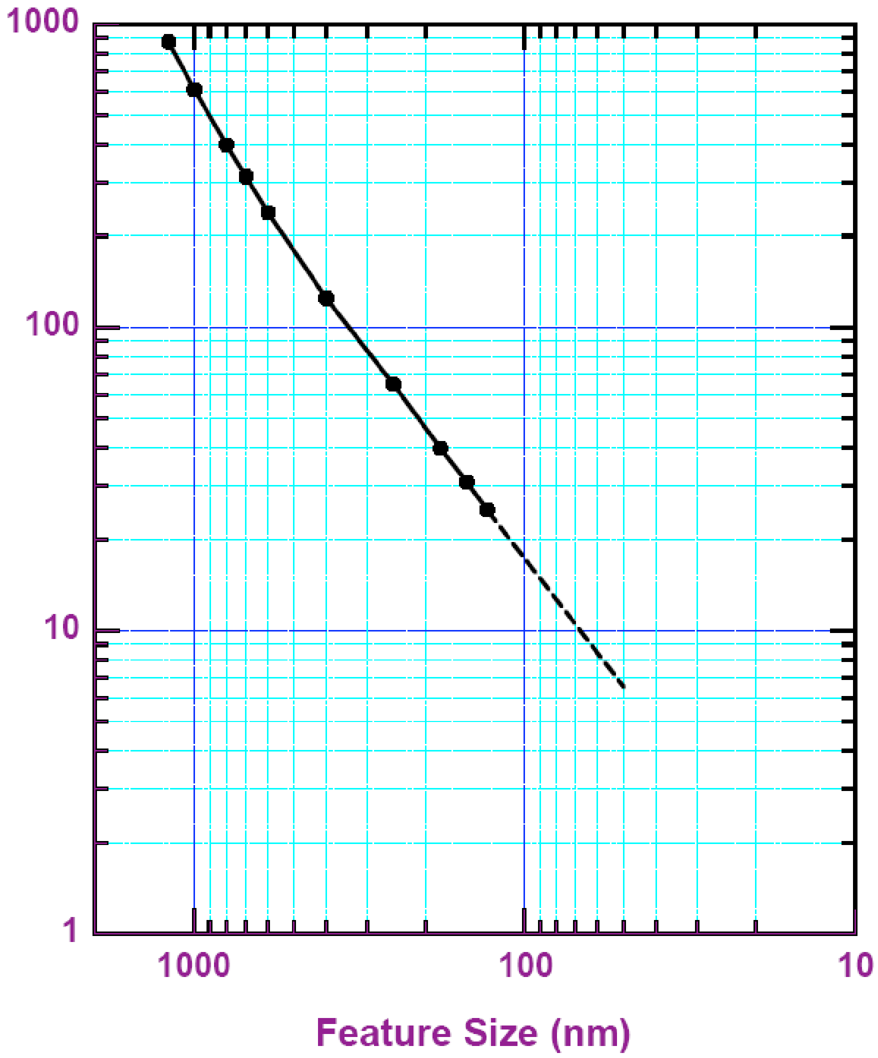
Types of SEEs

- Transient:
  - Single-event transient
  - Single-event upset
  - Single-event functional interrupt
- Destructive:
  - Single-event gate rupture
  - Single-event dielectric rupture
  - Single-event latchup
  - Single-event burnout

Single-event transients (Transients or SET)

- Radiation-induced charge temporarily changes the value of gate
  - No way to tell the difference from a real signal and a transient-affected signal
  - Transients in logic gates are a problem if latched, causes data corruption
  - Transients in the clock or reset trees can cause much more global issues
- Decreasing clock frequencies make it easier to latch a transient: transient pulse and clock signal are roughly the same

Critical Pulse Width for Unattenuated Propagation



Mavis, “Single-Event Transient Phenomena: Challenges and Solutions.” MRQW, 2002.

Single-Event Upsets (upsets or SEUs)

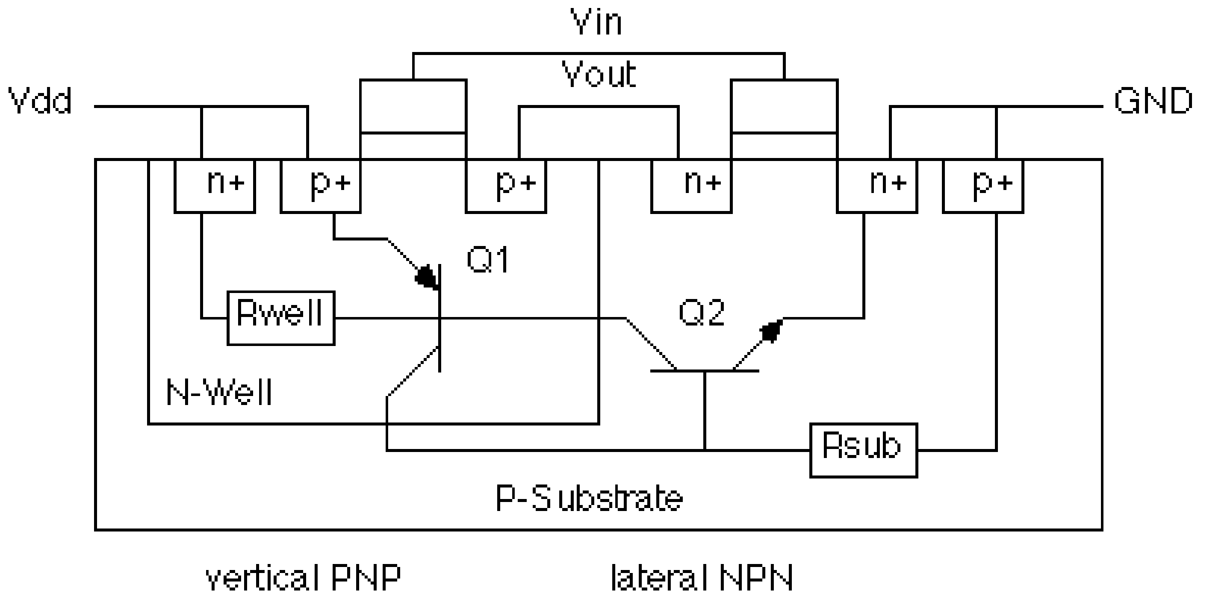
- Cause bit flips in memory-based
  - Data changes from 1→0 or 0→1
  - In some parts single-bit upsets (SBUs) are as common as multiple-cell upsets (MCUs)
    - Handy guide for MCUs:
      - All multiple SEUs are MCUs
      - Multiple-bit upsets are MCUs within a single word (memory) or frame (FPGA)
- Strongly affected by feature size:
  - Smaller feature size means smaller targets, smaller Qcrit, more MCUs
  - Even with a decrease in per-bit cross-section, often see an increase in per-device cross-section increase

Single-Event Functional Interrupts (SEFIs)

- Device will not operate functionally until reset
- Often caused by an SET or SEU in control logic for the device
- Causes availability issues as part will need to be reset to return to functionality

Single-event latch-up (SEL)

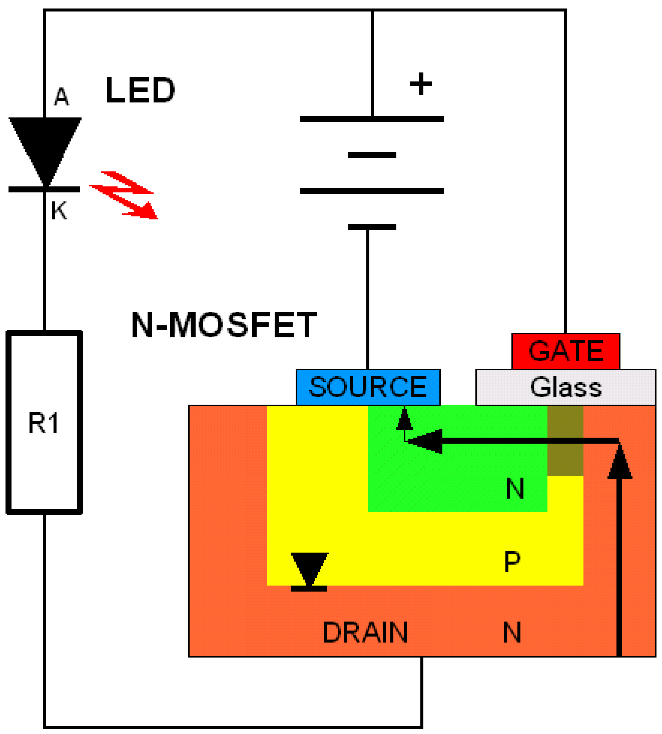
- Traditional reliability issue with CMOS due to parasitic transistors caused by well/substrate contact
  - Once turned on, current increases rapidly and destroys the part
  - Radiation is another avenue for turning on the parasitic transistor
- Military/aerospace parts often have an epitaxial layer to prevent SEL, by localizing charge collection



http://www.ece.drexel.edu/courses/ECE-E431/latch-up/latch-up.html

Single-Event Gate Rupture (SEGR)

- Common only in power MOSFETs
  - Occasionally seen in parts that have on-chip power, such as flash
- Ion-induced rupture of the gate oxide
- Destructive event – dielectric and gate electrode material “melt and mix”
- Ohmic short or a rectifying contact through the dielectric



Indirect Ionization

- SEEs can be caused by both direct ionization and indirect ionization
- Indirect ionization occurs when a particle hits the lattice and creates a nuclear fragment or a nucleus to be liberated from the lattice – nuclear recoil
  - In this case the the ionization is caused by the nuclear fragment and not the incident particle
  - Because the particle has to hit an atom head on to cause the nuclear recoil, devices are less sensitive to particles that cause indirect ionization

Indirect vs. Direct Ionization

- Because indirect ionization includes a direct strike to a Si atom, it is a much lower probability event than direct ionization
- The cross-sections for indirect ionization on the same part will be 5-7 orders of magnitude
- Particles or energy ranges of particles that cause direct ionization effects are a concern

Direct vs. Indirect Ionization: Particles

Particle	Direct	Indirect
Heavy ion	X	
Proton	< 3 MeV*	> 3 MeV

*Only 45nm and smaller devices

Low vs. High energy effects

Particle	Low	High
Heavy ion	direct	direct
Proton	direct*	indirect
Neutron	indirect	indirect

*Only 45nm and smaller devices

Low-energy proton effects

- Direct ionization from low-energy protons can be problematic, because low-energy protons are very abundant in both space and terrestrial environments
- Direct ionization effects from low-energy protons would greatly increase error rates

Protons vs neutrons

- Protons and neutrons have a lot of the same effect as each other, in terms of SEE
- In general, as a rule of thumb, the effect of a proton or a neutron above 10 MeV is equivalent
- Neutrons will never have a direct ionization effect because neutrons lack charge

Low-energy neutrons

- There are thermal neutron effects in some parts, though
- In those cases, the problem is not the neutron (per se) but the manufacturing of the part
  - Boron is very commonly in parts to reduce neutron effects
  - B10 has a sensitivity to thermal (low-energy) neutrons – B10 + n → Li7 + alpha – both the Li7 and the alpha can cause a SEE because the reaction is occurring in the sensitive volume

B10-contamination

- A “known” problem...that isn't disappearing
- Some parts in recent years have shown a wide range of B10 contamination from really bad to none
  - B10 is a price point in manufacturing but can be hard to get rid of

Cross-section

- Like TID, devices are tested to measure the cross-section
  - On-set: lowest LET/energy to cause the reaction
  - Saturation cross-section: the maximum sensitivity to the effect
- Most devices have one or some SEEs
  - Measurements of previous parts are not a good predictor of current parts – manufacturing, feature shrink, transistor design affects the sensitivity
  - There might be different on-sets and saturation cross-sections for different effects on the same device

Cross-section example (RTAX SET)

Typically SETs
Have a freq
relation

Saturation

Onset

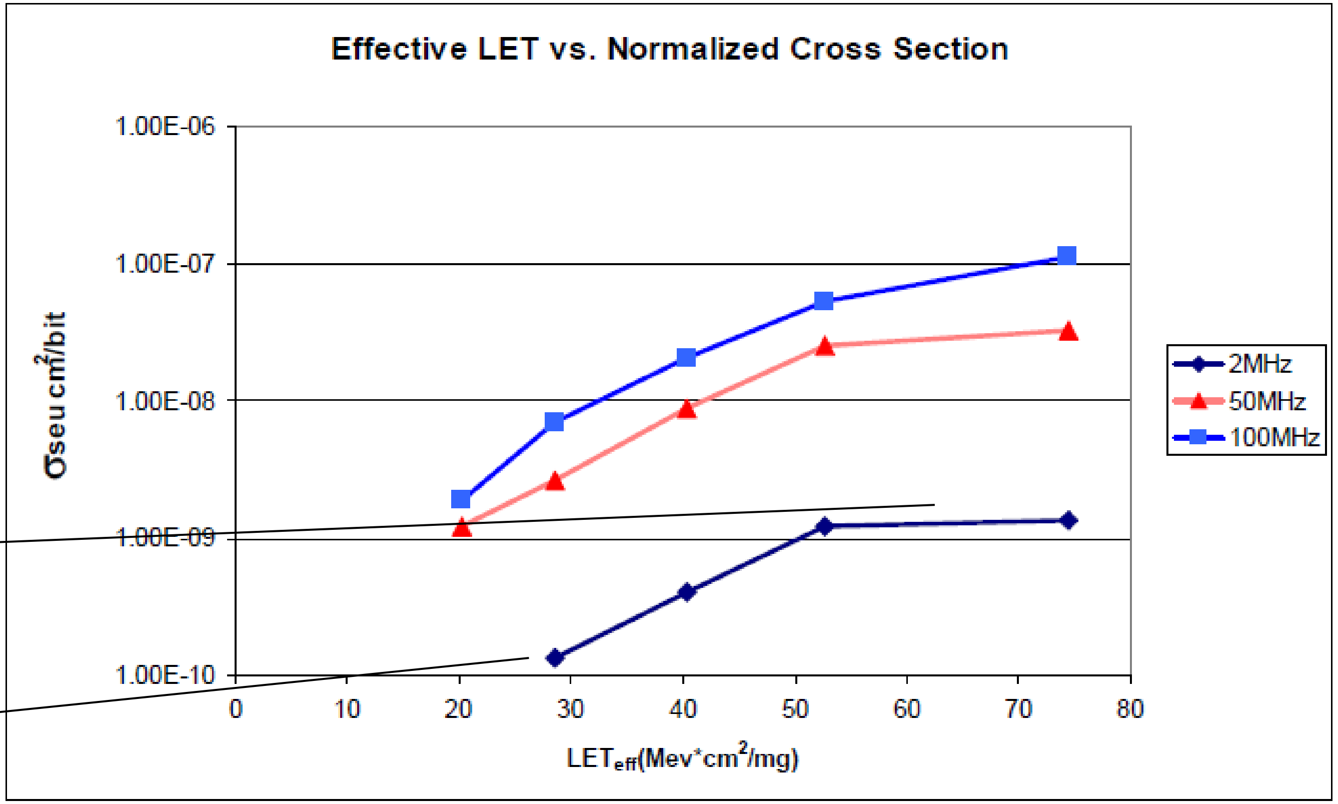


Figure 7: Comparison Cross Sections with respect to a spectrum on LET Values for Several Frequencies

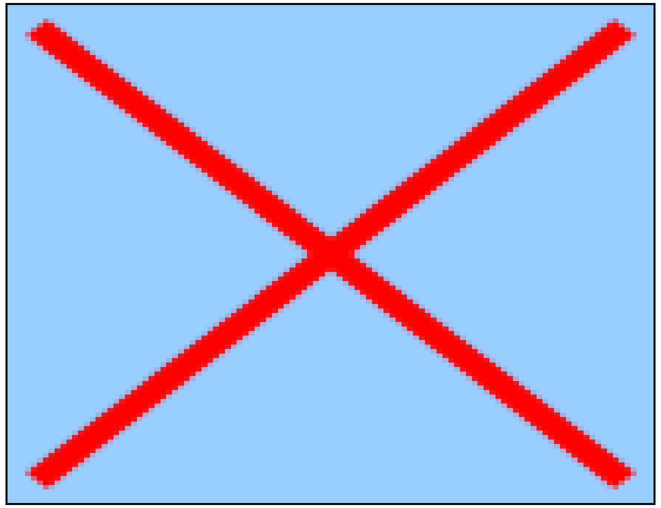
Cross-section and error rates

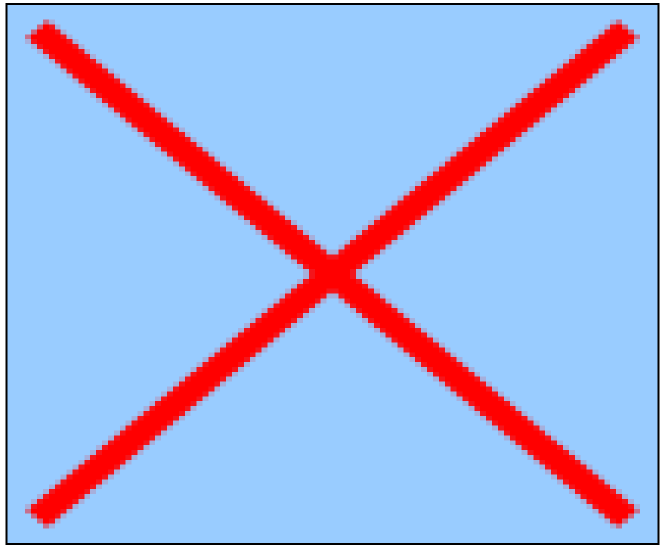
- The cross-section is combined with the environment in tools like CREME-MC to determine an error rate for the device in the environment
  - The error rate will help you determine whether mitigation is needed or not
- How does on-set affect error rates?
- How does the saturation cross-section effect error rates?

Cross-section vs. Range

- Range is an important part of testing for cross-section
- Remember that the sensitive volume is buried in the device
  - In space it doesn't matter that the sensitive volume is buried, because the particles have more kinetic energy than we can create in an accelerator
  - In testing to get an accurate measurement of cross-section, you must ensure that the radiation makes it to the sensitive volume otherwise the test is not accurate

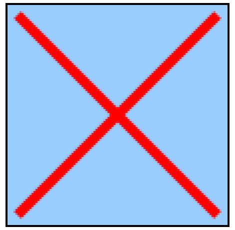
Sensitive Volume vs. Range





- In the top drawing, the radiation stops before it gets to the sensitive volume
- In the bottom drawing, the radiation gets to the sensitive volume, causing the charge generation to penetrate the sensitive volume
- It doesn't matter where it hits the sensitive volume – it just needs to get there

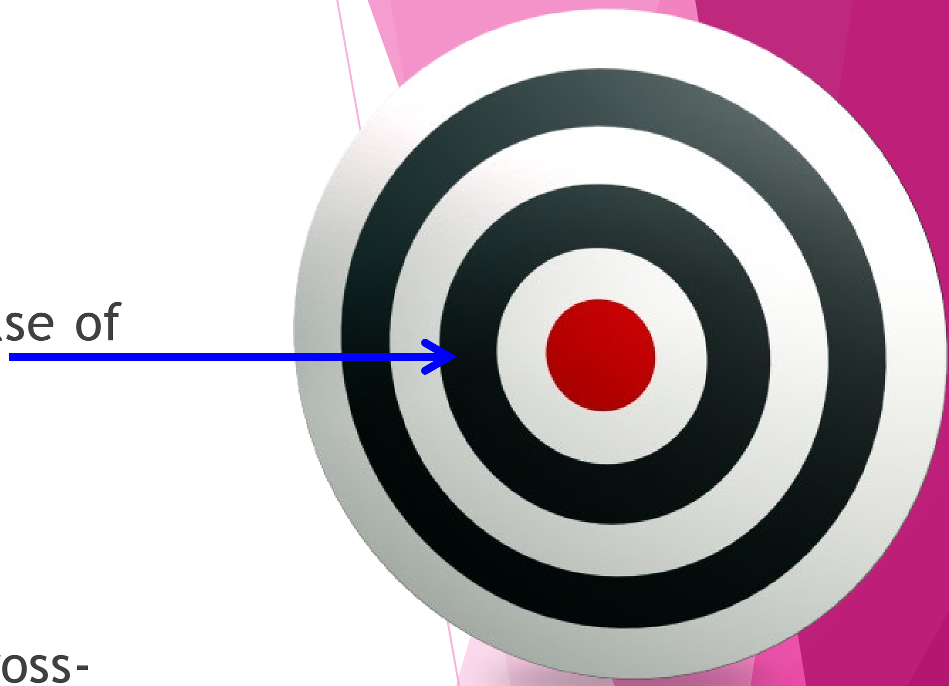
Angular Effects

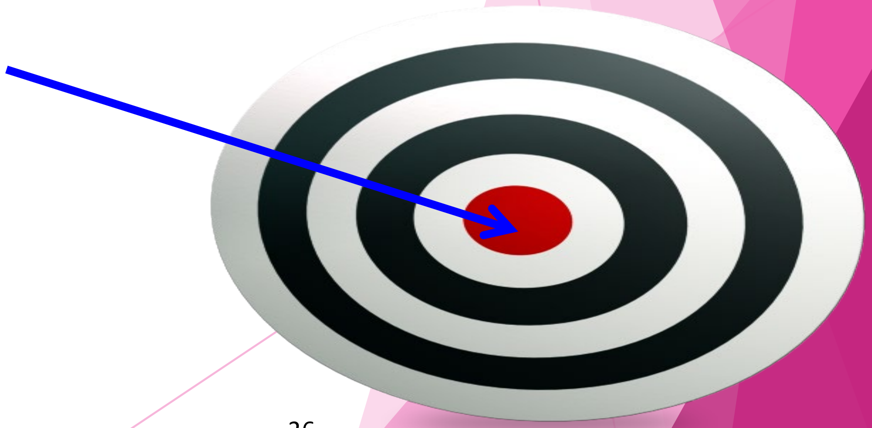


- In testing, some people will rotate the device in the beam to strike it at an angle
- What three things happen or could happen when you rotate the device?

Cross-section vs. Angle

- As long as you do not exceed the range of the ion, you get an increase of angle
- At the same time, the target shape changes
- It is now harder to hit the target
- The angle is taken into account in both the LET tested at and the cross-section – you don't want to mix the data





Angle Data on FPGAs

- Turns out that angle matters when testing FPGAs
- Many devices, especially SRAM, are very regular in their layout
- Not true for FPGAs – angular test results tends to highlight the heterogeneous layout
  - It's like mixing apples and oranges

Poisson Statistics

- “The probability of a number of events occurring in a fixed period of time if these events occur with a known average rate and independently of the time since the last event”
- One of the thing is predicts is the probability of a certain amount of radiation within a given time
  - Since Poisson statistics affects how much radiation emits at any given time, it affects the error rates
  - For TID the Poisson statistics mostly normalizes
  - For SEE the Poisson statistics causes constant variation in the error rates

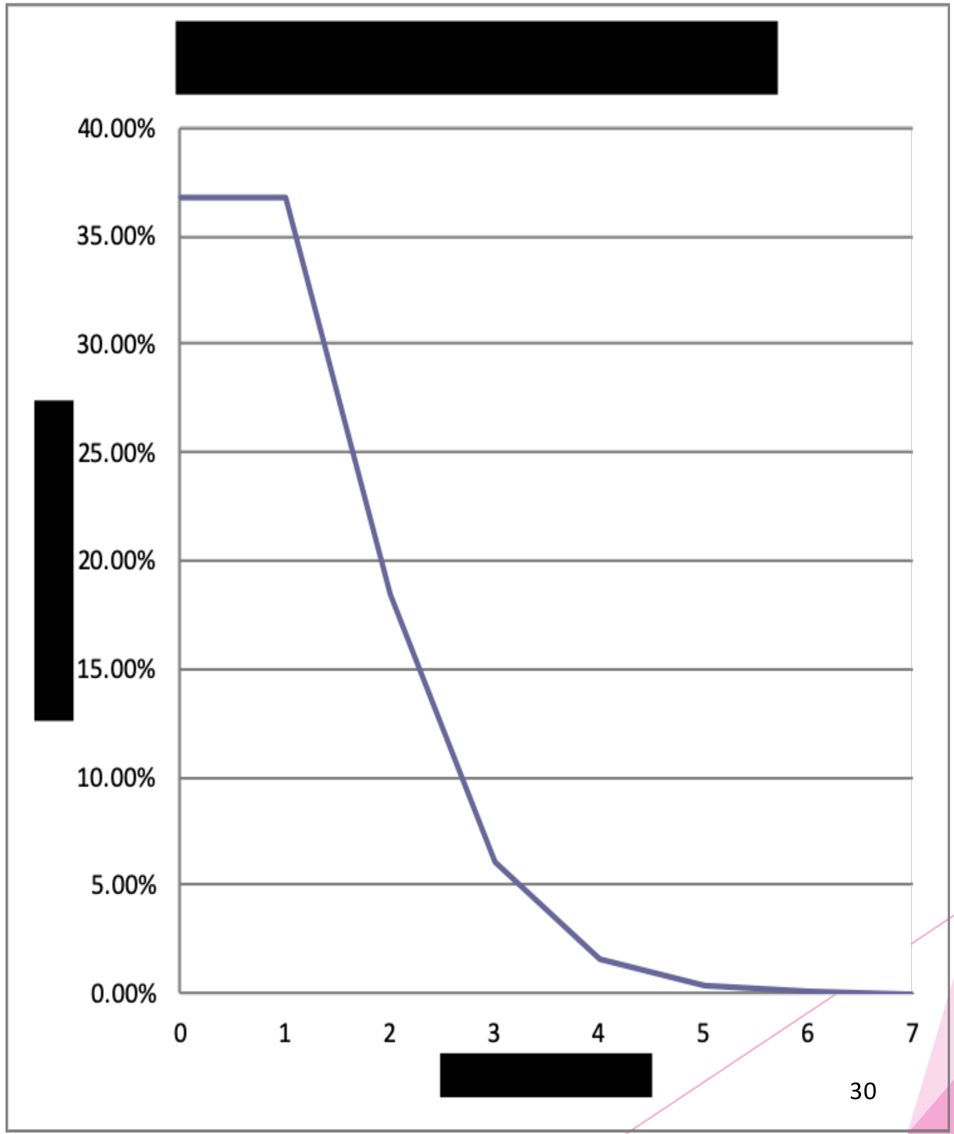
Poisson Probability Law

- The Poisson probability law tells us the probability that given
  - The average number of events per unit time, λ
  - The time τ, and
  - The number of events, k
- The probability of k events during time τ is

$$P(k; t, t + \tau) = e^{-\lambda t} \frac{(\lambda\tau)^k}{k}$$

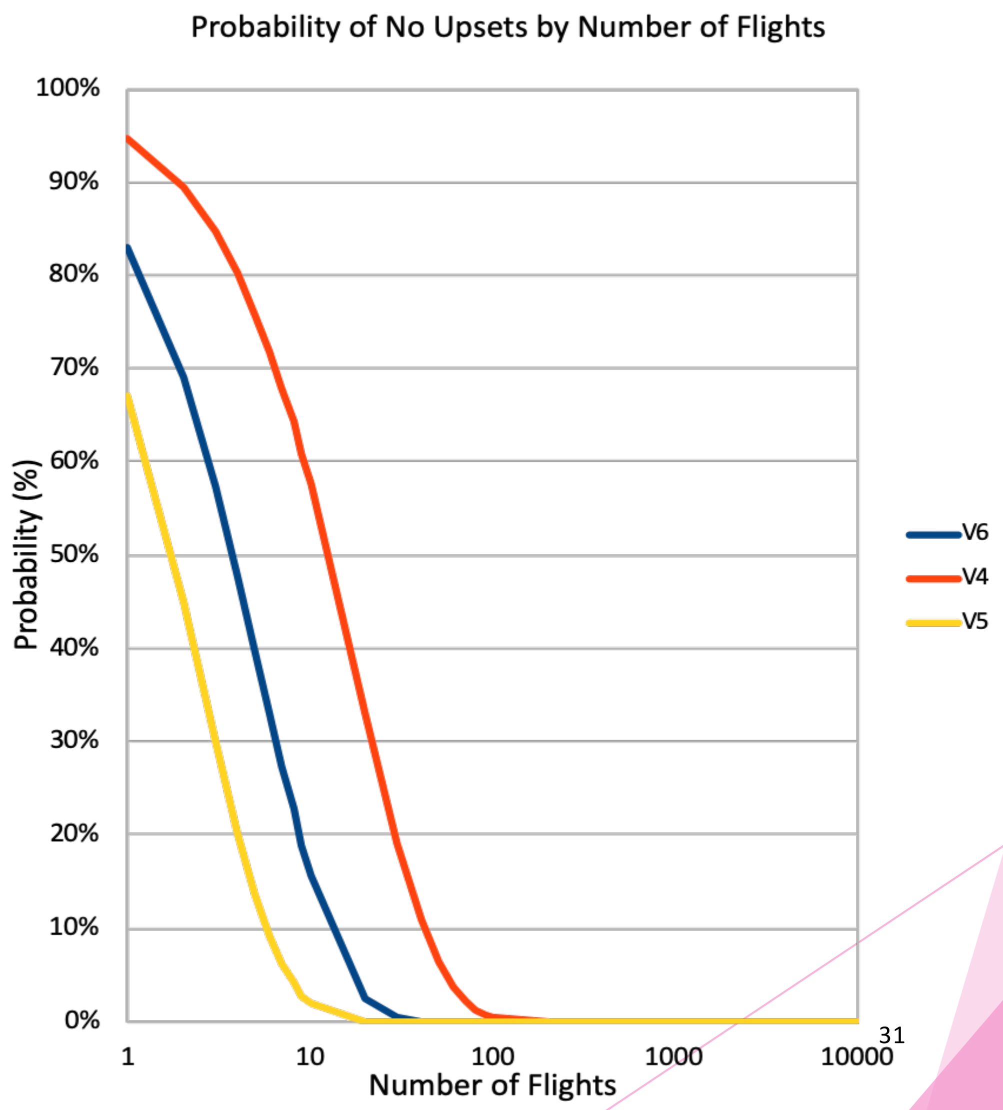
Inter-arrival time of SEEs

- Average rate only provides the “mean-average arrival rate” that upsets will occur at
- Errors will arrive based on the Poisson random process
  - MTTU gives the likely interval that errors will arrive at
  - Poisson determines when the errors will manifest
- There is an equal chance that no events and one event occur in one time period
- There is a 26% chance that 2 or more events occur



Inter-arrival time of SEEs

- Just because the sortie length < MTTU does not mean there will not be in-flight upsets
- At 20,000 feet, there is a 5% chance of having an upset in the first flight
- Each subsequent flight, it becomes increasingly less likely to not have an upset



Poisson Examples

- CREME-MC and QARM will provide you an estimate of what the error rate.
- You can convert that error rate into mean time to upset (MTTU) by inverting it:
  - MTTU = 1/SER
- Once you get to MTTU, then you can start asking questions like
  - Given time T, what is the probability that the system is still working?
  - Given time T, what is the probability that X upsets have happened?

What is the probability the system is still working?

- Assume that the system will fail if there are any errors. The error rate is 1 error per hour and we are interested in the first hour of operation. What is the chance that the system is still working in one hour?
- First off, our variables lambda and tau are:

$$\lambda = 1 errorperhour \qquad \tau = 1 hour$$

$$P(0errors; 0{,}1hour) = \mathrm{e}^{-1*1}\frac{(1*1)^0}{0!} = e^{-1} = .36$$

What is the probability the system is still working after two hours?

- Same setup, except tau is different
- First off, our variables lambda and tau are:

$\lambda = 1 error per hour$ $\tau = 2 hour$

$$P(0 errors; 0, 2 hour) = \mathrm{e}^{-1*2}\frac{(1*2)^0}{0!} = e^{-2} = .14$$

What is the probability there are two errors in 1 hour?

- Same setup, except k is different
- First off, our variables lambda and tau are:

$$\lambda = 1 error per hour \qquad \tau = 1 hour$$

$$P(0 errors; 0{,}1 hour) = \mathrm{e}^{-1*1}\frac{(1*1)^2}{2!} = \frac{e^{-1}}{2!} = .18$$